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## RESEARCH/REVIEW ARTICLE

# Historical ablation rates on south-east Greenland glaciers measured in the 1933 warm summer

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## Keywords

Surface mass balance; positive degree-days; climate change; Mittivakkat Glacier; Milthers; 7th Thule Expedition.

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## Abstract

Ice ablation rates measured on four glaciers in south-east Greenland in summer 1933 are recovered from an old field book of geologist K. Milthers. These unpublished ablation data are among the first measured in Greenland and were obtained during a warm period comparable to that of recent years. Ablation rates of up to 45 mm ice eq. d<sup>-1</sup> were observed. Using the Tasiilaq meteorological record, we calculate degree-day factors of ca. 3–5 mm ice eq. d<sup>-1</sup>°C<sup>-1</sup>. Comparing these results with 1996–2012 observations at one of Milthers' glaciers (Mittivakkat), we find that ablation rates and degree-day factors are significantly higher (61 ± 50%) in recent years. We speculate this to be due to a reduction in surface albedo, and perhaps the retreat of the glaciers out of the cold maritime inversion layer. Our findings suggest that using a temperature-index method that assumes constant degree-day factors may produce inaccurate long-term ablation estimates for south-east Greenland glaciers, further emphasizing the value of the rare 1933 measurements for validation of ablation models.

To access the supplementary material for this article, please see the supplementary file under Article Tools, online.

In the Tasiilaq region of south-east Greenland, the Little Ice Age ended around 1900 (Humlum & Christiansen 2008). A warm period occurred in the 1930s (Hanna et al. 2012), with several summers ranking among the warmest of the 20th century (Box 2002). Historical ice ablation measurements taken during this warm period are highly valuable to provide perspective on the response of Greenland glaciers to atmospheric warming. Unfortunately, very few historical measurements are known to exist for the 1930s.

Knud Rasmussen's 7th Thule Expedition (1933) in part took place in the Tasiilaq (then Angmagssalik) region (Fig. 1). The expedition applied the latest technologies available at the time, such as a photo-theodolite and photography of the landscape from hydroplanes in order to map the area. Geologist Keld Milthers (1907–1960) was a member of the expedition with the research objective to

study glaciers and their relation with landforms. Milthers made a reconnaissance, photo-documenting 15 glaciers and their surroundings. The terminus areas of five glaciers were documented by images taken with a photo-theodolite. Sites on these glaciers were marked with flagged bamboo stakes to facilitate mapping. These stakes were also used to determine ablation throughout the melt season. Preliminary ice ARs were published by Gabel-Jørgensen (1935), who gave estimates of the total ice ablation over a period of two months (1.18 and 1.42 m), but without mentioning specific glaciers.

Milthers' field book containing all 1933 data has been in custody of the University of Copenhagen since 1957 (Milthers 1933). It formed a basis for reinitiating the study of Mittivakkat Glacier (Milthers' glacier 7) by B. Frisrup at the Institute of Geography in 1958 as a Danish contribution to the International Geophysical Year.

**Abbreviations in this article**

AR: ablation rate  
DDF: degree-day factor  
PDD: positive degree-day

Fristrup (1960) called the area representative of the East Greenland climate and reported a 400–500 m retreat of the terminus over a period of 25 years, but did not publish information on ice ablation.

When in 2009 Milthers’ glass theodolite plates were found at the Danish Cadastral Institute, the possibility arose to pinpoint the exact locations of the glaciers in 1933, greatly enhancing the value of the ablation observations. In 2010, the Milthers Memorial Expedition took place, revisiting and photographing the same glaciers as surveyed in 1933. A comparison between the old and new photographic material revealed that the termini of glaciers in this part of Greenland had retreated up to 1500 m since 1933 (Kjær 2013). During the memorial expedition, Milthers’ field book was instrumental in locating the old glaciers and theodolite positions. A note in the field book revealed that Milthers himself had attempted to summarize stake observations from four of the five glaciers in order to calculate ablation.

This inspired us to analyse all stake data found in the field book. Milthers’ detailed notations made it possible to determine the time and place of each stake reading, allowing us to calculate the ARs in an historical ablation study.

Coincidentally, Milthers’ observations took place during one of the warmest East Greenland summers in the previous century. Figure 2 shows that the 1933 summer in Tasiilaq was especially warm, and that the average summer temperature of nearly 7°C in the 1930s was in the range of temperatures recorded since the mid-1990s. In this paper, we use the 1933 stake observations of Milthers to verify if the ARs and DDFs for that year differed from those measured in recent warm years. Therefore the aim of this paper is not only to present the unpublished historical ice ablation measurements from south-east Greenland, but also to compare them with data from the recent warm period.

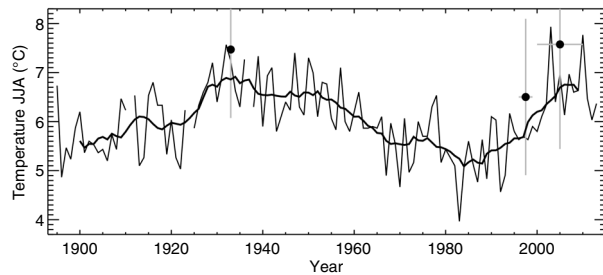
**Methods**

**1933**

Milthers selected five glaciers for detailed investigation with a photo-theodolite (nos. 5, 6, 7, 8 and 15; Fig. 1,



**Fig. 1** The location of Milthers’ glaciers and the meteorological station in Tasiilaq. Source: map 650 1 and 2 (original scale 1:250.000) by the Danish Institute of Geodesy, mapped 1932–33, revised in 1945 and 1969. Contour intervals 50 m. (Reproduced with permission of Kort & Matrikelstyrelsen, G 15-99.)



**Fig. 2** Summer (June, July, August) average temperatures (thin line) and 10-year running mean (thick line) in Tasiilaq (Cappelen 2014). The dots indicate the average temperatures during this study's observational periods in 1933, 1996–99 and 2000–2010. Horizontal grey lines indicate the time span, vertical ones the standard deviations.

Table 1), forming a cross section from the Greenland ice sheet to the outer coast. Four of the five glaciers were equipped with bamboo poles drilled approximately 0.5 m into the ice. The locations of the stakes were marked in sketches in his field book (Fig. 3a), and the glaciers were photographed (Fig. 3b). Each glacier was visited two to four times during the melt season (mostly in August) and equipped with two to four stakes. In Milthers' notebook, the distance from the top of a stake to the ice surface is noted with 1 or 5 mm precision, on which we base a measurement accuracy of  $\pm 5$  mm (Supplementary Table S1). The time of day of each stake reading was not always noted down; when missing it is estimated from travel times from locations with time notation, the accuracy of which we estimate at  $\pm 3$  h. Therefore, the shorter the time spans between stake readings, the larger the relative uncertainty; as an example of worst-case uncertainty we take the shortest time record from glacier 8:  $\pm 3$  h on 120 h yields an uncertainty of  $\pm 2.5\%$ . Combining this with the uncertainty in the stake reading ( $\pm 5$  mm on 120 mm, i.e., 4.2%), total uncertainty on ARs equals  $\pm 5\%$ . We consider this maximum uncertainty to apply to all historical ARs. Additional uncertainty was introduced for some stake readings on glacier 7 as stakes had melted out, which we consider minimum values.

Milthers did not perform meteorological observations at the glaciers, but the Danish Meteorological Institute did, in Angmagssalik (now Tasiilaq) at 10–50 km distance

from the glaciers (Cappelen 2014). We acknowledge that the Tasiilaq record does not represent the actual temperature at each glacier, but it does enable us to compare different time periods. From this record daily-average temperatures are calculated by the European Climate Assessment & Data project (available at [www.ecad.eu](http://www.ecad.eu)). We calculate PDD totals for each ablation period by summing the above-freezing daily-average temperatures. Positive degree values for days with stake measurements were proportionally divided using the time of the stake reading. To again determine the upper limit in the uncertainty, we calculate the PDD for the short 120 h ablation period at glacier 8 to be  $30.8^{\circ}\text{C}$  and find an uncertainty due to the timing of the measurement of  $\pm 3.0\%$ . A DDF expressing the ice ablation per degree-day is calculated by dividing the ablation with the PDDs between stake readings. The combined uncertainty in the stake reading (4.2%, see above) and the timing of it again results in  $\pm 5\%$ , which can conservatively be applied to all DDF values.

### 1996–2012

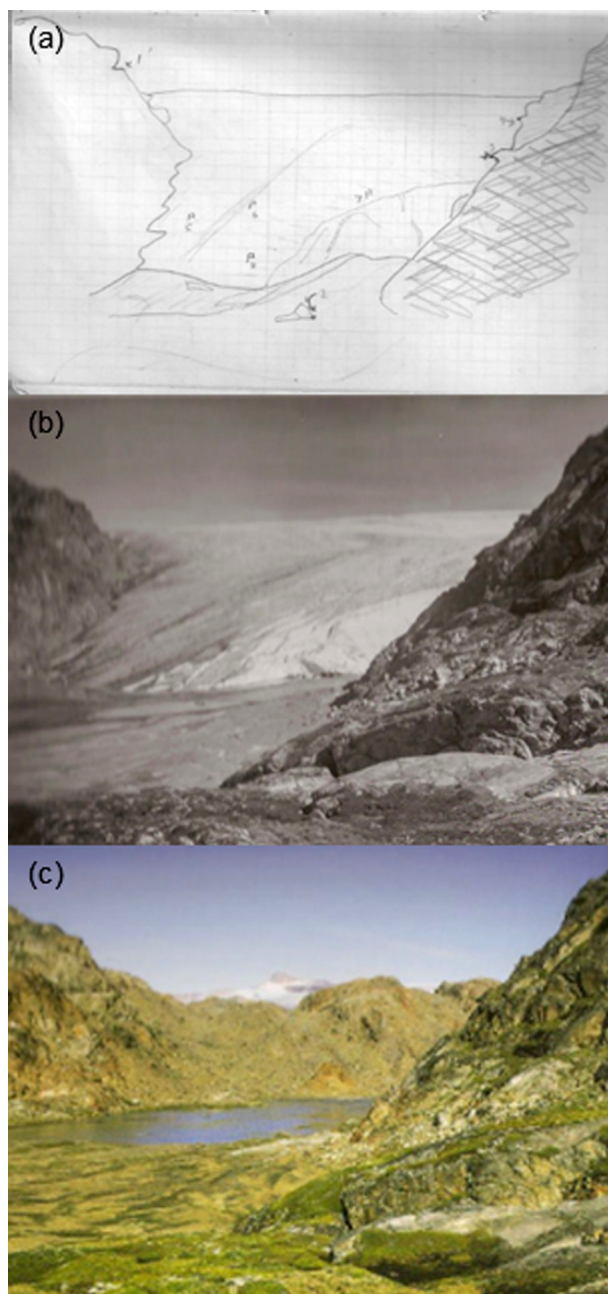
More recent investigations of ablation in the region have been carried out only on Mittivakkat Glacier (glacier 7) (Hasholt & Jakobsen 2008; Knudsen & Hasholt 2008). The glacier is instrumented with a stake network consisting of 5.5 m aluminium stakes drilled 5 m into snow or ice, generally measured once (in late summer) or twice (also in spring) per year (Mernild, Liston et al. 2008). These records cannot be used for comparison with Milthers' measurements because the latter are for bare ice only, except at one stake (Supplementary Table S1). However, in several years some of the stakes near the glacier terminus were measured more than once during the summer, when bare ice had surfaced at the measurement sites. Also reports from field courses in 1998, 2009 and 2010 list the short-term ablation using 20 cm long ice screws, allowing a comparison with Milthers' ablation values (e.g., Hasholt & Nielsen 1998; Kroon et al. 2011).

Because of the possible heating by solar radiation both the stakes and the ice screws were insulated at the bottom, successfully preventing self-drilling. However, as

**Table 1** UTM coordinates (zone 24W) and altitudes of the glacier termini in 1933 and 2010, including the terminus retreat over the period. The coordinates and altitudes represent the lowest position of each glacier. Glacier 8 values are unknown.

| Glacier | UTM north/west | Altitude (m a.s.l.) | UTM north/west | Altitude (m a.s.l.) | Horizontal retreat (m) |
|---------|----------------|---------------------|----------------|---------------------|------------------------|
|         | 1933           | 1933                | 2010           | 2010                | 1933–2010              |
| 5       | 7302582/532408 | 38                  | 7302137/533446 | 69                  | 826                    |
| 6       | 7299868/536691 | 58                  | 7299339/536235 | 78                  | 686                    |
| 7       | 7284578/550081 | 7                   | 7284366/551344 | 98                  | 1283                   |
| 15      | 7318041/598107 | 28                  | 7319097/597490 | 67                  | 1112                   |





**Fig. 3** Mittivakkat Glacier (7). (a) Sketch and (b) photograph from 1933 (Milthers 1933), and (c) photograph from 2010 (N. Jacup Korsgaard), all taken from the same location near the coastline. The terminus was at 7 m a.s.l. in 1933 (Table 1); with the surrounding valley walls being about 200 m high, stakes are estimated to have been at 20–50 m above the terminus elevation.

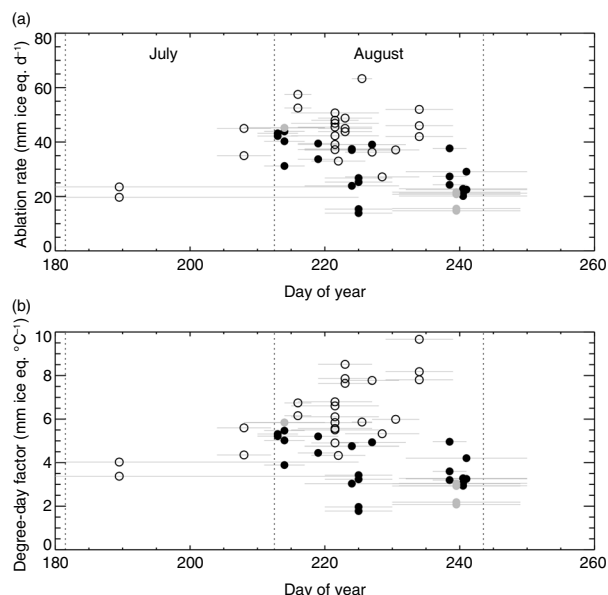
opposed to the bamboo that Milthers used, solar heating causes cone-like depression around the modern-day stakes and ice screws. A ruler is therefore placed on the undisturbed surface around the depression and its level used in the ablation determination. Repeated measure-

ments indicate a precision of 5–10 mm depending on the surface roughness. As with the 1933 data, the recent ablation measurements were converted into ablation totals and rates. The PDD and DDF values were again determined using Danish Meteorological Institute temperature recordings in Tasiilaq. The uncertainties on PDDs and DDFs are assumed equal to the maximum uncertainty of 5% determined for 1933.

## Results

The measurements of ablation and the calculated ARs, accumulated PDDs and DDFs are given in Supplementary Table S1. For glacier 5, the calculated 1933 average AR is  $36 \pm 7$  mm ice eq.  $\text{d}^{-1}$  (standard deviation indicated). Similarly, for glaciers 6, 7 and 8 the values are, respectively,  $31 \pm 9$ ,  $28 \pm 13$  and  $30 \pm 7$  mm ice eq.  $\text{d}^{-1}$ . For glacier 7, we calculate an average AR of  $43 \pm 10$  mm ice eq.  $\text{d}^{-1}$  for 1996–99, and  $45 \pm 7$  mm ice eq.  $\text{d}^{-1}$  for 2000–2010. Values from 2012 are not included in the calculations because of the comparatively long period between measurements. Because of the small sample size and the relatively large standard deviations these AR averages are not significantly different at the 95% level. There is also no significant difference between the two recent periods from glacier 7. However, the AR values from glacier 7 do differ significantly (99% level) between 1933 and the recent periods. The average of all 1933 AR values is  $31 \pm 10$  mm ice eq.  $\text{d}^{-1}$ , revealing a present-day increase of  $43 \pm 46\%$  using the average AR values from glacier 7 in 1996–2010 ( $44 \pm 8$  mm ice eq.  $\text{d}^{-1}$ ). If we only take into account the 1933 glacier 7 values (which are mostly minimum values), we find an increase of  $59 \pm 63\%$ .

As mentioned, the PDD values for the period between two stake readings are calculated from the temperature record from the meteorological station in Tasiilaq, the representativeness of which we will discuss in the following section. In Fig. 4, the timing and length of the observation period within the year is indicated for each observation pair. The average daily temperature calculated over the observational period in 1933 (27 July–7 September) was  $7.5 \pm 1.4^\circ\text{C}$  (Fig. 2). The more recent observations are again divided in two periods since the summers in the 1990s appear relatively cool in Fig. 2. We find an average temperature of  $6.5 \pm 1.6^\circ\text{C}$  for the observational period in 1996–99, and of  $7.6 \pm 2.1^\circ\text{C}$  for 2000–2010 (the 1996–2010 observational period average is  $7.0 \pm 1.9^\circ\text{C}$ ). We find no significant difference between the mean temperatures from the 1930s and the more recent observation period, which allows us to compare DDF values between these periods.



**Fig. 4** ARs (a) and DDFs (b) calculated from ablation measurements in 1933 (dots) and recent years (circles) (Supplementary Table S1). Horizontal grey lines represent the corresponding periods. Grey dots illustrate minimum-value measurements.

We calculate 1933 DDF values to be  $4.7 \pm 0.7$  mm ice eq.  $d^{-1}^{\circ}C^{-1}$  (glacier 5),  $4.0 \pm 1.0$  mm ice eq.  $d^{-1}^{\circ}C^{-1}$  (glacier 6),  $3.7 \pm 1.7$  mm ice eq.  $d^{-1}^{\circ}C^{-1}$  (glacier 7), and  $3.9 \pm 0.9$  mm ice eq.  $d^{-1}^{\circ}C^{-1}$  (glacier 8). Because of the limited number of observations from each glacier and the relatively large standard deviations, the differences between the DDF values are not significant at the 90% level. As mentioned, the DDFs are calculated for periods of different lengths from late July until early September 1933. In Fig. 4, it appears that DDF values decreased during the 1933 melt season. To investigate, we subdivide the 1933 data into three periods (excluding “minimum” values): July/early August, mid-August, and late August/September. The DDF values for these periods are  $4.9 \pm 0.6$  mm ice eq.  $d^{-1}^{\circ}C^{-1}$  (seven observations),  $3.6 \pm 1.3$  mm ice eq.  $d^{-1}^{\circ}C^{-1}$  (nine observations) and  $3.6 \pm 0.7$  mm ice eq.  $d^{-1}^{\circ}C^{-1}$  (eight observations), respectively, declining in time but also not deviating significantly from each other at the 90% level. Recent data from the Mittivakkat Glacier give DDFs of  $6.5 \pm 1.3$  mm ice eq.  $d^{-1}^{\circ}C^{-1}$  for 1996–99 and  $6.5 \pm 1.6$  mm ice eq.  $d^{-1}^{\circ}C^{-1}$  for the slightly warmer 2000–2010 period, revealing no difference between the two periods. A Student t-test indicates that with 95% probability the recent DDF values exceed those from 1933. The average 1933 DDF value is  $4.0 \pm 1.3$  mm ice eq.  $d^{-1}^{\circ}C^{-1}$ . With a DDF average of  $6.5 \pm 1.4$  mm ice eq.  $d^{-1}^{\circ}C^{-1}$  for 1996–2010, this yields an increase of  $61 \pm 50\%$ .

## Discussion and conclusions

Table 1 lists the coordinates and altitude of the termini of Milthers’ glaciers in 1933 and 2010, and their retreat over the period, as determined from rectified and georeferenced photographs from 1933 and recent satellite images. The stakes are estimated to have been located 25–100 m above the altitude of the termini. Milthers’ glaciers are spaced 5–60 km apart, but they have several features in common. (1) They all have termini in proximity of coast lines and (2) the altitude of the termini is quite similar; in 1933 termini altitudes ranged from 7 to 58 m a.s.l., and in 2010 from 67 to 98 m a.s.l. (Table 1). (3) Their local climate has the same characteristics in terms of the frequent occurrence of relatively cold sea breezes and coastal fog caused by an atmospheric inversion layer over water (Mernild & Liston 2010). Also, (4) glaciers 5, 6, 7 and 8 are all relatively sheltered from solar radiation, either by being north-east facing (5, 6 and 8) or confined to a rather narrow valley (7). Due to the similar setting of the glaciers it is reasonable to assume that they will react similarly to temperature changes. The similarity between the glaciers is also suggested by the fact that there is no statistically significant difference in ablation between the four glaciers. We therefore posit that glacier 7 (Mittivakkat) can be taken as representative of near-coastal, relatively well-shaded glaciers within the area. The wider representativeness of the Mittivakkat Glacier is also argued by Fristrup (1960) and Mernild, Liston et al. (2008). Naturally there are also differences between the glaciers. For instance, the glacier trunks of 5, 6 and 8 are steeper than those of 7 and 15. The relatively flat valleys in which glaciers 7 and 15 are located (and perhaps the fact that glacier 15 is south-facing) is likely why they experienced the largest horizontal retreat ( $>1$  km) since 1933 (Table 1).

Stake data from both periods are only available for glacier 7. While no local observations of temperature were performed at the glaciers in 1933, temperature has been measured at glacier 7 at the coast and at 515 m a.s.l. since 1996. At the coastal weather station (25 m a.s.l.), the yearly average temperature was  $-0.74 \pm 0.69^{\circ}C$  for the period 1998–2006 (Mernild, Hansen et al. 2008). In the same period, the temperature in Tasiilaq was  $-0.17 \pm 0.64^{\circ}C$ , yielding that the temperature difference between the two stations is not statistically significant. Considering that the altitude (Table 1) and the distance to the coast of the ablation measurements in 1933 are similar to those of the meteorological station in Tasiilaq (ca. 50 m a.s.l.), it is reasonable to assume that Tasiilaq temperature can be used to calculate the 1933 DDF values for each glacier. A complicating factor is the retreat of the glaciers since 1933, which under a negative

adiabatic temperature lapse rate would cause the current glacier termini to be at higher, colder altitudes relative to 1933. For instance, recent stakes at glacier 7 are located at altitudes of ca. 200 to ca. 350 m a.s.l. (lowest ones listed in Table 2)—all higher than the Tasiilaq meteorological station. However, due to the above-mentioned atmospheric inversion layer, lapse rates at glacier 7 are measured to be  $+1.2^{\circ}\text{C km}^{-1}$  in summer (Mernild, Hansen et al. 2008), indicating that the temperature at the recent stakes may instead be  $0.2$  to  $0.5^{\circ}\text{C}$  higher than in Tasiilaq and at the glacier terminus in 1933. Yet with the period-average temperature of ca.  $7^{\circ}\text{C}$ , as reported in the previous section, an increase in temperature of  $0.2$ – $0.5^{\circ}\text{C}$  cannot explain the 43% increase in ablation from 1933 to 1996–2010.

A potential issue when using longer time series such as the Tasiilaq temperature record is that homogeneity breaks may have occurred on account of changes in instrumentation, calculation methods or relocation of the meteorological station. These changes combined can be in the order of a few tenths of a degree Celsius in Tasiilaq (John Cappelen, pers. comm.). Unfortunately no other records from the region exist to perform a homogeneity test. However, we calculate that in order to have matching DDF values for 1933 and recent years, a temperature offset exceeding  $4.5^{\circ}\text{C}$  would be required. This indicates that our conclusions are valid well beyond the temperature measurement uncertainty.

We determined that temperatures for the ablation measurement periods in late July to early September were similar in both 1933 and the recent period, indicating that the temperature forcing of ablation within the early warm period and the present are similar. Therefore it is reasonable to compare ARs and DDFs from 1933 with recent values, which have increased by an average of 43% and 61%, respectively. Since temperatures are not dissimilar, the increased DDFs are caused by increased ARs, which must be due to changes in an energy flux that is not directly dependent on air temperature, solar radiation being the most plausible candidate. For instance, we theorize that the glacier retreat causes the termini to move to a higher altitude above the sea, reducing the shading by often-present low-level fog and thus increasing solar radiation absorption.

**Table 2** UTM coordinates (zone 24W) and altitude ranges of recent stakes on glacier 7 for 2008. The horizontal variation due to the annual redrilling of the stakes is within 50 m.

| Stake | UTM north/west | Altitude<br>(m a.s.l.) | Surface lowering (m)<br>1996–2008 |
|-------|----------------|------------------------|-----------------------------------|
| 40    | 7285154/551762 | 202                    | 35                                |
| 41    | 7285384/551643 | 207                    | 30                                |
| 42    | 7284937/551811 | 202                    | 35                                |

This cannot be quantified without further measurements. Alternatively, increased radiation absorption may be the result of a lower glacier surface albedo. Mernild et al. (2015) calculate a slight albedo decrease of up to  $-0.04$  in the lower regions of Mittivakkat Glacier between 2000 and 2013, but this can only explain part of the increased DDFs. We would need long-term observations of radiation and albedo to confirm the importance of solar radiation on changing DDF values.

In this study, we have presented results in units of ice equivalent because no ice density measurements were performed by Milthers in 1933. For converting the data into units of water equivalent, we recommend using an ice density of  $890\text{ kg m}^{-3}$ , a value which was determined at Mittivakkat Glacier in recent years. Note that from a similar ice density measurement in an area with many cryoconite holes a single value was found to be as low as  $690\text{ kg m}^{-3}$ . In spite of this, we argue that the ablating ice surface has a rather constant density, but that there is small-scale spatial variability in ARs due to dust, soot, bacteria, solar radiation penetration, etc. that lowers the mean surface density of the ice as it ablates down. It must be stressed that the DDFs presented in this study are for bare ice and should not be applied to situations with a seasonal snow cover present.

Based on our results, we recommend against applying temperature-index methods using constant DDF values in studies covering a period of decades, particularly when including both the 1930s and recent decades. If a larger suite of measurements had been available for this study, a surface energy balance approach that resolves all energy fluxes would have been the best choice. The main advantage of using DDFs is that it requires only one measured variable and thus can help generate ablation estimates over long time periods. Therefore it is unfortunate that we find historical DDF values to differ from present-day ones. If DDFs determined in recent years were to be used for calculating ablation over time scales of decades or more, historical ARs and mass loss from south-east Greenland glaciers would be overestimated by  $61 \pm 50\%$ . This emphasizes the importance of Milthers' 1933 stake measurements, which can provide important validation of reconstructed historic ablation in Greenland.

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